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Evaluation of Reliability of the Earthquake Resistant Building Provided by means of the Analysis for Design-Basis Earthquake

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Abstract

The paper analyzes the reliability level realized through the method recommended by SP 14.13330.2014 (Seismic Building Design Code). The results of the probabilistic analysis of a 16-storeyed earthquake-resistant building in terms of the action of the seismic load correspondent to the design basis earthquake are given. The analysis was carried out on the basis of standard computational procedures of the FEM, computerized in modern software packages for analysis, which are used in design practice. The comparison of the analysis results of two building models was carried out, both with and without regard to foundation beds deformations.

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Keywords: Seismic risk; earthquake resistance; reliability; effective period;

Nomenclature

$\sigma_{\sigma c}$	is the standard for stresses
Λ	frequency of earthquakes occurrence
$S_u(\omega)$	spectral density of displacement
$\varphi_k(z)$	forms of natural oscillations
η_{jk}	coefficients of form
N	number of oscillation forms recorded
$\xi_j(t)$	generalized coordinates function

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c_j	attenuation coefficient
λ_j	j-th natural oscillation frequency of the system
$\ddot{\tilde{H}}_j(t)$	generalized random load

1. Structure

The design and analysis of earthquake-resistant buildings are connected with a high-degree uncertainty of the basic design parameters of seismic load: the moment of earthquake origination, amplitude, spectral content, duration are random values or functions with the variation value of 30-40%. According to [1], a lower design level of reliability should be set for such loads, since additional expenses aimed at obtaining a high level of reliability are not efficient when the design parameters are highly uncertain. In fact, the probability of failure (risk) of earthquake-resistant building structures in the case of design-intensity earthquake occurrence is 2-3 times higher than the probability of the building structural failure due to regular loads [2]. The limit state method [3] providing a generally high reliability level of buildings and constructions does not allow evaluating this level quantitatively. This requires a transition from the limit state method to the direct method of reliability analysis based on the ultimate allowable risk. And here the numerical value of reliability of building and constructions both under design and operation can be obtained only through the application of probabilistic models. The issues of the seismic reliability evaluation of building and constructions applying the risk parameter are insufficiently covered in specialized literature. As a rule, the evaluation of building reliability under seismic impact is restricted to the evaluation of the risk of foundation bed's seismic acceleration exceedance over the design level [2]. The existing probabilistic methods were primarily developed for one-dimension cantilever-pendular models of constructions as well as for seismic load models as one-dimension stationary random processes in the form of white noise or with latent periodicity [4-9]. At the same time, constructions work like entire spatial systems under the action of seismic loads. Nowadays, through the use of modern applied software packages for structural analysis realizing the FEM algorithms, the analysis of constructions of any complexity degree is carried out, including their probabilistic analysis for the action of random seismic loads [10-14]. To construct a reliability function, it is necessary to carry out approximately 10^4–10^5 tests which is awkward to be used in design practice. Therefore, the development of engineering methods evaluating the seismic reliability of buildings and constructions is a topical issue. The works [15,16] give the engineering method of the seismic reliability analysis of buildings and constructions, developed by the authors, which allows obtaining the quantitative evaluation of building vulnerability as well as designing buildings of preset reliability level applying approximate dependences of the random processes theory and standard procedures of building analysis for seismic loads, computerized in modern software packages. Using this method, let us evaluate the reliability level provided by SP 14.13330.2011 (Seismic Building Design Code) [17] within the analysis of buildings for design–basis earthquake. A 16-storeyed residential building is being considered. The building' height is h=48 m. It is square in ground plan, with the dimensions of 24x24 m. The building foundation is a cast-in-situ reinforced concrete slab 1000 mm thick. The columns are of 400x400 mm in section, stiffness diaphragms are 200 mm thick. The structural concrete is of B25 class, reinforcement bars of A240, A400 classes are applied for the reinforcement of building elements. The analysis of the building is carried out with Lira 9.6. software package. The analytical model (fig.1) consists of the following types of finite elements: FE 10 being a multi-purpose bar FE for spatial problem, FE 42 being a multi-purpose shell triangular FE, FE 44 being a multi-purpose shell rectangular FE. The design seismic activity of the site is of magnitude 7 according to A OSR-97 map (Seismic Regions map). The seismic load is considered to be the product of stationary random function $\tilde{X}(t)$ by nonrandom envelope function $A(t) = A_0 e^{-\gamma t}$ [5] (fig.2).

$$\ddot{\tilde{H}}(t) = A_0 e^{-\gamma t} \tilde{X}(t) \qquad (1)$$

The random function $\ddot{\tilde{H}}(t)$ is set by the spectral density

$$S_H(\omega) = D_H \frac{2\alpha}{\pi} \frac{m^2 + \omega^2}{m^4 + 2a\,\omega^2 + \omega^4}\ ,\ m^2 = \alpha^2 + \beta^2, \quad a = \alpha^2 - \beta^2 \qquad (2)$$

The spectral density parameters are as follows α=6 s^{-1}, β=14 s^{-1}. The root mean square ground acceleration $\sigma_H = \sqrt{D_H}$, peak amplitude of oscillations $\ddot{H}_{\max} = 100$ cm/s^2 and amplitude coefficient *A=0,1* are set in accordance with the current norms [17]: Earthquake intensity - 7 magnitudes, σ_H = 25 cm/s^2.

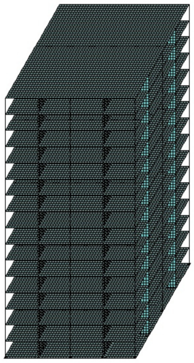

Fig. 1. Analytical model of building

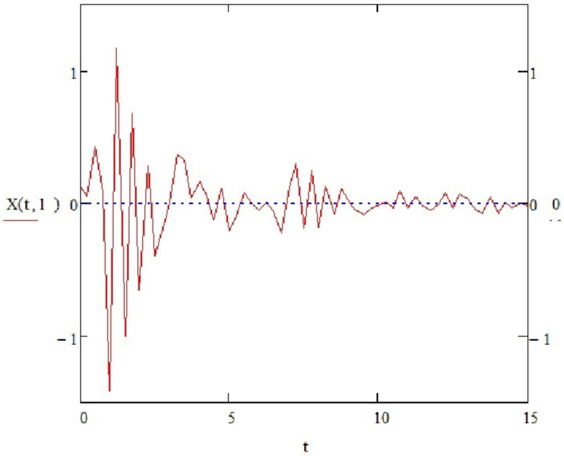

Fig. 2. Variant of earthquake accelerogram

Earthquake attenuation coefficient γ=0,3 [18]. The analysis is carried out for the two types of dynamic analytical model: with and without regard to the interaction between the building and foundation bed. The elastic stiffness coefficients of the foundation bed are determined with regard to longitudinal and transverse velocities of elastic waves in soil. The deformable foundation bed is adopted with the stiffness coefficients C_{1z}=7000 kH/m^3 C_{2z}=70000 kH/m. The oscillations of the design space system under seismic load are described by the differential equation:

$$\ddot{\xi}_j(t) + 2c_j\dot{\xi}_j(t) + \lambda_j^2\xi_j(t) = -\ddot{\tilde{H}}_j(t) \text{ , } i=1,2...N \quad (3)$$

The dynamic characteristics of the system for the two variants of the analytical model are given in table 1.

Table 1. Natural frequencies of building

№ of form	Deformable foundation bed			Non-deformable foundation bed		
	Circular frequency, (rad/s)	Period, (s)	Coefficient of form	Circular frequency, (rad/s)	Period, (s)	Coefficient of form
1	3.418	1.838	1.392	5.485	1.146	-0.112
2	3.418	1.838	0.329	5.485	1.146	1.487
3	3.850	1.632	0.000	5.673	1.107	0.000
4	20.460	0.307	0.000	26.439	0.238	0.000
5	22.414	0.280	-0.333	26.464	0.237	-0.061
6	22.414	0.280	0.283	26.464	0.237	-0.730
7	22.915	0.274	0.000	33.842	0.186	0.000
8	25.282	0.249	-0.226	42.525	0.148	0.000
9	25.282	0.249	-0.220	42.525	0.148	0.001
10	29.844	0.211	0.000	46.370	0.136	0.000

Taking into account that the system under consideration is a resonance filter, the generalized coordinates dispersions can be found through the approximated formula [19]

$$D_{\xi j} = \frac{\pi S_H\left(\lambda_j\right)}{4c_j\lambda_j^3} \tag{4}$$

Tables 2 and 3 show the standards of stresses and displacements in the most loaded elements.

Table 2. Stresses in elements

Stresses, kPa, when z=0.		
№ of element	Deformable foundation bed	Non-deformable foundation bed
14	-5089.88	-2182.19
28	-2021.69	-6654.19
38	-8422.75	-11653.3
58	-5734.06	-1101.56
65	-2587.44	-5573.56

Table 3. Node displacements in the system

Displacements, mm, when z=h.		
№ of node	Deformable foundation bed	Non-deformable foundation bed
403, 407, 409, 413, 415, 419, 421	-74.05	-34.19

I
n order to construct the reliability function, we apply the formulas of the theory of runs [20].

$$U_k\left(u_{\max}.t\right) = \frac{1}{T_{ek}\left(t\right)}\exp\left(-\frac{u_{\max}^2}{2\sigma_{uk}^2\left(t\right)}\right) \tag{5}$$

For resonance filters, the formula of the effective period of change of displacement function for *k*-th mass of space system has the form [15]

$$T_{ek}(t) = 2\pi \left[\frac{\int_0^\infty S_u(\omega) d\omega}{\int_0^\infty \omega^2 S_u(\omega) d\omega} \right]^{\frac{1}{2}} \approx 2\pi \left(\frac{\sum_{j=1}^{N} \left(\frac{\varphi_k^2(z) \eta_{jk}^2 S_H(\lambda_j)}{\lambda_j^3} + \right)}{\sum_{j=1}^{N} \left(\frac{\varphi_k^2(z) \eta_{\xi k}^2 S_H(\lambda_j)}{\lambda_j} + \right)} \right)^{\frac{1}{2}} \tag{6}$$

The values of the effective period for the *j*-th form of oscillations are given in table 4.

Table 4. Effective period

№ of form of oscillations	Values of effective period T_{ek}, s deformable foundation bed	Values of effective period T_{ek}, s non-deformable foundation bed
1	1.838	1.146
2	1.838	1.146
6	0.28	0.237

The integrated effective period is

$$T_{ek_\Sigma} = \sqrt{\sum_{j=1}^{N} \left(T_{ek_j} \right)^2} \tag{7}$$

For the analytical model with deformable foundation bed $T_{ek_\Sigma} = 2.615$ s. For the analytical model with non-deformable foundation bed $T_{ek_\Sigma} = 1.637$ s.

$$\lambda_{ek_\Sigma} = \frac{2\pi}{T_{ek_\Sigma}} \tag{8}$$

Due to the linear character of the analysis operator, the effective period of change of displacement random function equals to the effective period of change of random stress-and-force function

$$T_{e,uk}(t) = T_{e,\sigma k}(t) \ . \tag{9}$$

Then the average number of runs $U_c(R_b, t)$ of stress function over the level R_b.

$$U_c(R_b, t) = \frac{1}{T_{e,\sigma k}(t)} \exp\left(\frac{R_b^2}{2\sigma_{\sigma c}^2} \right) \tag{10}$$

The conditional probability that stresses in the section will exceed the level R_b during a design-basis earthquake at least once at the time $0 \le \tau \le t$ equals to

$$P\left(\sigma_{\sigma,c} > R_b \middle| t \right) = 1 - \exp\left(-\int_0^t U_c\left(R_b \middle| t \right) d\tau \right) \tag{11}$$

Taking into account the hazard level of the territory, the total seismic risk is

$$P_{seism}\left(R_b,T\right)=P\left(\sigma_{\sigma,c}>R_b\left|t\right.\right)H\left(T\right)=\left\{1-\exp\left[-\int_0^t U_c\left(R_b\left|\tau\right.\right)d\tau\right]\right\}\left[1-\exp\left(-\Lambda T\right)\right] \tag{12}$$

The results of the analysis of both the conditional and total seismic risks for particular elements of the analytical model are given in table 5.

2. Main results and conclusions

- The reliability analysis of a 16-storeyed cast-in-situ residential building with braced frame structure for the seismic load of magnitude 7 showed the following:
  1. in the most loaded sections the conditional probability of failure (vulnerability) due to stress exceedance is 0,292÷0,316 and 0,386÷0,456 during the first seconds of earthquakes for modules with deformable and non-deformable foundation beds respectively. Taking into account the earthquake duration for the moment of time t=10s, the conditional probability of failure averagely amounts to 0,973 and 0,996, while the total probability of failure amounts to 0,098 and 0,099 respectively. Thus, the model of foundation bed elastic rigidity adopted in the design code does not significantly influence the value of the structural failure probability;
  2. the probabilistic analysis of the stress-strain state of the most loaded building structures shows that the probability of their failure due to strength loss is close to 1. It does not seem possible to find it out through deterministic analyses applying the limit state method.
- The method for the seismic reliability evaluation of building and constructions, developed by the authors, does not require a direct probabilistic analysis to be carried out. It is oriented to the application of any of the structural analysis software packages realizing the FEM and to the maximum use of standard procedures of earthquake-resistant buildings analysis, which are adopted in the design code. Therefore, it can be recommended for engineering practice.

Table 5. Seismic risk parameters

№ of element	Intensity of runs $U_c\left(R_b,t\right)$		Conditional risk, deformable foundation bed $P\left(\sigma_{\sigma,c}>R_b\left|t\right.\right)$		Conditional risk, non-deformable foundation bed $P\left(\sigma_{\sigma,c}>R_b\left|t\right.\right)$		Total seismic risk $P_{seism}\left(R_b,T\right)$			
							when t=1 s		when t=10 s	
	Deformable foundation bed	Non-deformable foundation bed	when t=1 s	when t=10 s	when t=1 s	when t=10 s	Deformable foundation bed	Non-deformable foundation bed	Deformable foundation bed	Non-deformable foundation bed
14	0.368	0.607	0.308	0.975	0.455	0.998	0.031	0.046	0.097	0.099
28	0.380	0.572	0.316	0.978	0.436	0.997	0.032	0.044	0.098	0.099
38	0.345	0.501	0.292	0.968	0.394	0.993	0.029	0.039	0.097	0.099
58	0.365	0.610	0.306	0.974	0.456	0.998	0.031	0.046	0.097	0.099
65	0.379	0.584	0.315	0.977	0.442	0.997	0.032	0.044	0.098	0.099

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